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Flow Manipulation of a Fin on a Flat Plate Interaction in High-Speed Flow by Means of Micro Flaps

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14. ABSTRACT
Previous work has been done by Massey and Bell of protuberances on fin-body interactions of high speed projectiles. Both computational and experimental analysis has shown that significant force multiplication can exist by modifying the boundary layer shock interaction of the fin and body. The devices used in these previous studies were relatively large (on the order of one third the fin height) and protruded beyond the boundary layer. The purpose of this study is to show the effects of multiple micro flap devices on the fin and flat-plate interaction problem. The aerodynamic mechanisms could then be incorporated into micro adaptive flow control schemes to control a projectile. Computational fluid dynamics will be used to analyze various configurations, including a validation against experimental data from Massey. Study of the various configurations will help to determine critical features and flow qualities necessary for favorable interactions.

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Flow Manipulation of a Fin on a Flat Plate Interaction in High-Speed Flow by Means of Micro Flaps

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Previous work has been done by Massey[1-3] and Bell[4] of protuberances on fin-body interactions of high speed projectiles. Both computational and experimental analysis has shown that significant force multiplication can exist by modifying the boundary layer shock interaction of the fin and body. The devices used in these previous studies were relatively large (on the order of one third the fin height) and protruded beyond the boundary layer. The purpose of this study is to show the effects of multiple micro flap devices on the fin and flat-plate interaction problem. The aerodynamic mechanisms could then be incorporated into micro adaptive flow control schemes to control a projectile. Computational fluid dynamics will be used to analyze various configurations, including a validation against experimental data from Massey[1]. Study of the various configurations will help to determine critical features and flow qualities necessary for favorable interactions.

Nomenclature

CFD   =   Computational Fluid Dynamics
MAFC   =   Micro Adaptive Flow Control
psi   =   pounds per square inch gage pressure
psia   =   pound per square inch absolute pressure
y-star   =   boundary layer height measurement utilized to compare boundary layer profiles and grid sizing

I. Introduction

THE study of boundary layer shock structure interaction has been the focus of a vast amount of research in high-speed flows. Understanding these interactions is critical to the application of Micro Adaptive Flow Control (MAFC) to high-speed flows. Creating favorable interactions between small scale devices and the structures around which they are placed will allow for the augmentation of control forces with relatively small force inputs from the devices. This typically requires optimization of the devices to a given structure. A basic understanding of the critical features required to produce favorable interactions is the focus of a recent Computation Fluid Dynamics (CFD) experiment. A flat plate was chosen to produce a reflection surface for a generic fin. Variations in micro-flap structures on the fin and flat plate will be optimized to produce maximum force.

A baseline CFD validation case was run based on the geometry used by Massey in a wind tunnel experiment. CFD Data is compared to this experimental force and pressure measurements. The CFD study is then extended to the application of micro-flaps in fixed positions located on both the surface of the fin and flat plate. Optimized configurations will then be studied further to determine critical flow properties that yield favorable interaction between the fin, flat plate and micro flap structures.

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II. Baseline Validation Case

A baseline validation case was constructed based on the geometry develop by Massey[1]. The geometry selected mimicked the configuration where a pin 0.2 inches in diameter and a height of 0.5 inches was located 0.6 inches from the trailing edge of tapered fin mounted on a flat plate. The fin was exposed to Mach 1.7 flow from a round jet in the experimental setup shown in Figure 1. Detailed flow conditions from the jet are not described in the paper and are therefore estimated for the CFD validation case.
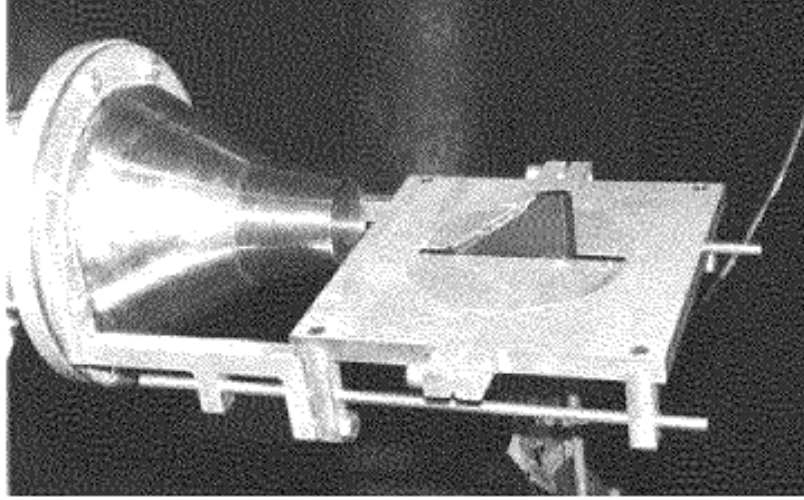

Figure 1. Experimental test setup at GTRI Hot-Jet Facility.

The CFD grid for this configuration is shown in Figure 2. The grid was generated using ANSYS Gambit 2.4.6. The grid utilizes a tetrahedral mesh in the far-field with structured prism mesh at the near-wall surfaces with a
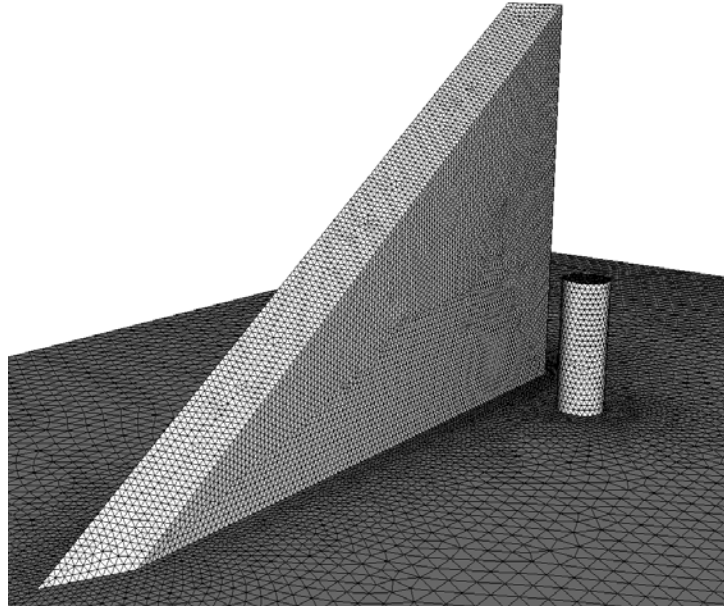

Figure 2. CFD grid of fin and pin found in reference 1. Pin is 0.2 inches in diameter, 0.5 inches high, and 0.6 increase from rear of fin.

starting cell height of 0.003 mm. The grid consists of 2.2 million cells. The CFD solution was run using ANSYS Fluent 6.3.26 on 16 processors on an IBM System x3650/x3550 cluster. The 3-D solution utilized the density-based explicit steady-state double-precision solver. The fluid medium was modeled as ideal gas air with standard properties at standard sea-level atmospheric conditions.. The k-omega SST turbulence model was used to model near wall and far-field turbulence. The near-wall boundary-layer mesh was on the order of y-star of one. The k-

omega SST turbulence model utilizes a blended approach that allows the near-wall effects to modeled directly with the grid without compromising far-field effects. This is done with a blending function that models the near-wall directly (or with a k-omega model if sufficient grid does not exist to model it directly with y-star above 1) and then models the far-field with a k-epsilon turbulence model.

This is accomplished through the use of a blending function that gradually turns the k-omega model into a k-epsilon model in the far-field. The benefit to this type of turbulence model in high-speed flow is better prediction of boundary-layer interaction and separation as is the case with the current configuration. Second order discretization is utilized for the flow equations, turbulent kinetic energy, and specific dissipation rate. The solution was run until solution residuals were reduced three orders of magnitude.

Table 1 shows a comparison of side force from the experimental results and CFD. The experimental results produced 6.61 lbs of net side force on the fin and the CFD prediction produced 8.39 lbs of net side force on the fin.

	Side Force (lbs)	Axial Force (lbs)
Fin Test	6.61	
Fin CFD	8.39	7.41
Pin CFD	-0.25	4.00

Table 1. Table comparing experimental results of CFD results.

The experimental force was determined by assigning areas to each of the 28 pressure taps on the pin side of the fin and then integrating to determine the force on that side of the fin. In addition, forces were not calculated on the the sharp rear and front edges of the fin due to the fact no instrumentation was located here. How the force was determined for the lee-ward side of the fin was not documented in Massey's report. Because pressure data was not
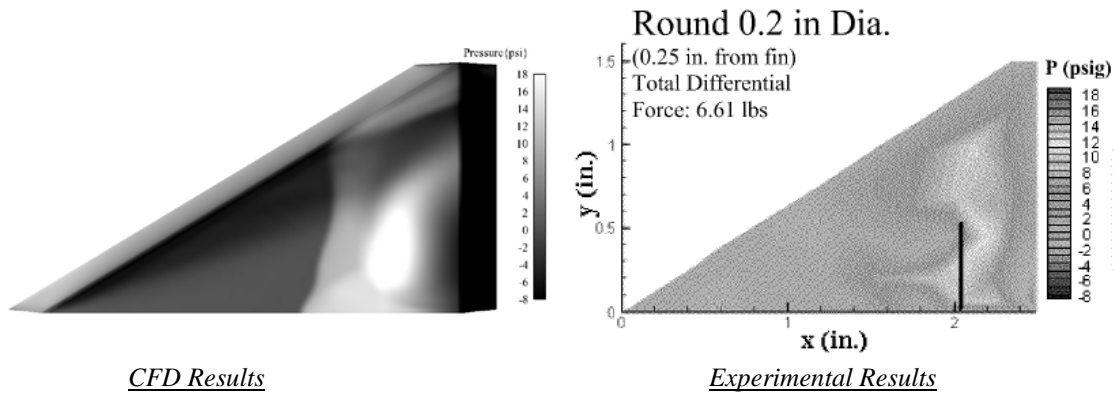

CFD Results   Experimental Results

Figure 3. CFD pressure contour of fin on pin side.
Experimental results taken from Figure 20 in reference 1.

available on the lee-ward side of the fin, some experimental error could have resulted. In addition, the photo in Figure 1 seems to indicate that the entire fin may not have been completely submerged in the Mach 1.7 flow stream as was the case for the CFD model. Overall, CFD results compared favorably to experimental results. In addition, the CFD analysis determined a net axial force on the fin and pin of 7.41 and 4.00 lbs respectively. The pin produced a side force in the opposite direction of the fin of 0.25 lbs. The drag on the pin and the opposing side force are deleterious effects that would not have been known from wind tunnel testing.

The pressure contours from the CFD on the fin are compared to the experimental test results. The effects from the pin can be seen in both cases, however the pin produces higher peak pressures near the pin in the CFD model. This could be another reason for the significant difference in the results between the two cases. The resolution of the CFD model is significantly finer than the 28 pressure taps utilized in the experimental test setup. As a result, distinct shock features can be seen on the fin in front of and behind the pin. These strong shock interactions are likely what produced the significant side forces. It appears this is an important aspect of making this type of concept to work effectively.

Figure 5 shows pressure contour levels on the pin side of the fin in psi. As can be seen, pressures are very high on the fin near the location of the pin at the rear, reaching almost 22 psig pressure. The shock structure upstream of
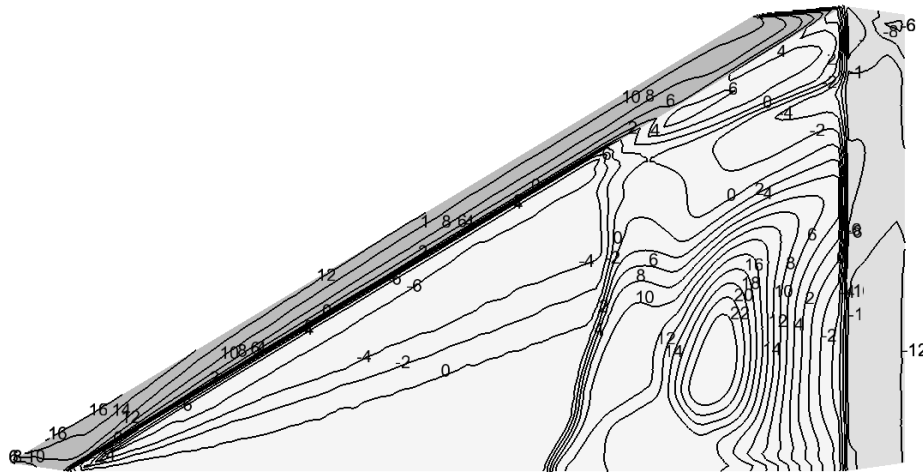
Figure 5. Pressure contours of pin side of fin. Contour levels in psig.

the pin can be seen by the close spacing of the contour levels indicating a discontinuity. An expansion downstream of the local high pressure near the pin can be seen as well. The rapid expansion around the sharp corners of the fin can also be seen at both the front and rear of the fin.
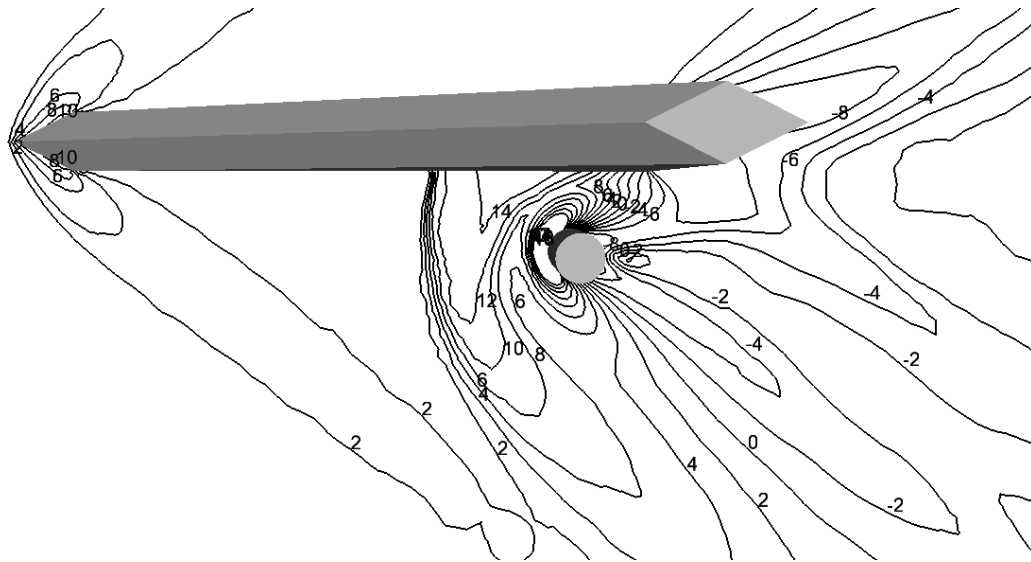

Figure 6. Pressure contours of flat plate. Contour levels in psig.

Figure 6 shows pressure contour levels on the flat plate in psig. The flow is moving from left to right across the fin and pin. The fin and pin are shown above the contour. The effects of the pin and fin can be seen on the flat plate. A relatively sharp shock can be seen at the leading edge of the fin. The shock can be seen to be slightly detached near the leading edge and forming a small bow structure.

The bow structure on the round pin is significant. A small bow shock is detached from the pin approximately one-half of a pin diameter upstream. This detached shock then appears to cause second detached shock approximately two to two-and-a-half pin diameters upstream of the pin. This shock could likely be a result of shock interaction and reflections from the pin. Understanding these interactions is critical to maximizing control forces. In addition, the close proximity of the pin to the fin causes a contraction of the flow between the pin and fin. This contraction increases the pressures on both the fin and pin in this area. As the flow exits this area, it expands. Ensuring that this expansion occurs behind the fin is critical to maximizing forces.

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III. Micro Flap Study

A CFD experiment was conducted with micro flaps on the baseline fin and flat plate configuration developed by Massey[1]. For the first case, the Mach Number is fixed at 1.7 as it was in the Massey study. The first micro flap configuration is shown in Figure 7. The height of the four micro flaps is 5 mm, the width 3 mm and the
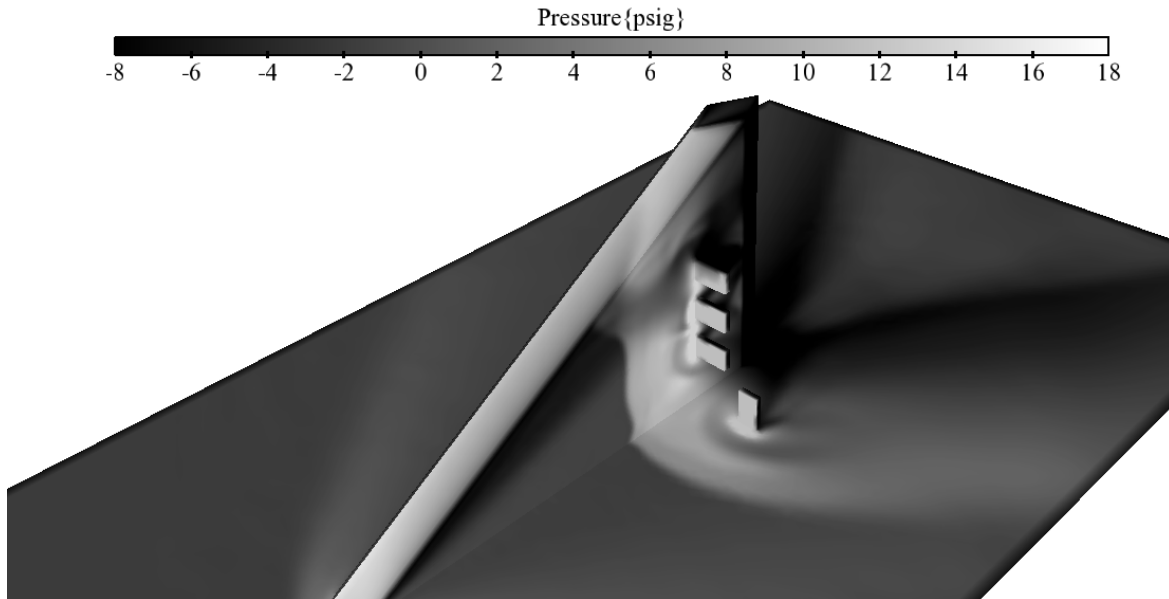

Figure 7. Baseline micro flap pressure contour (psig). Three micro flaps located on fin and one micro flap on flat plate. Micro flap on flat plate in same location as Massey study.

thickness 1 mm in the streamwise direction. The flap on the flat plate is in the same location as in the baseline pin study. The flaps on the fin are 6 mm apart center to center with the bottom flap 7 mm from the flat plate.
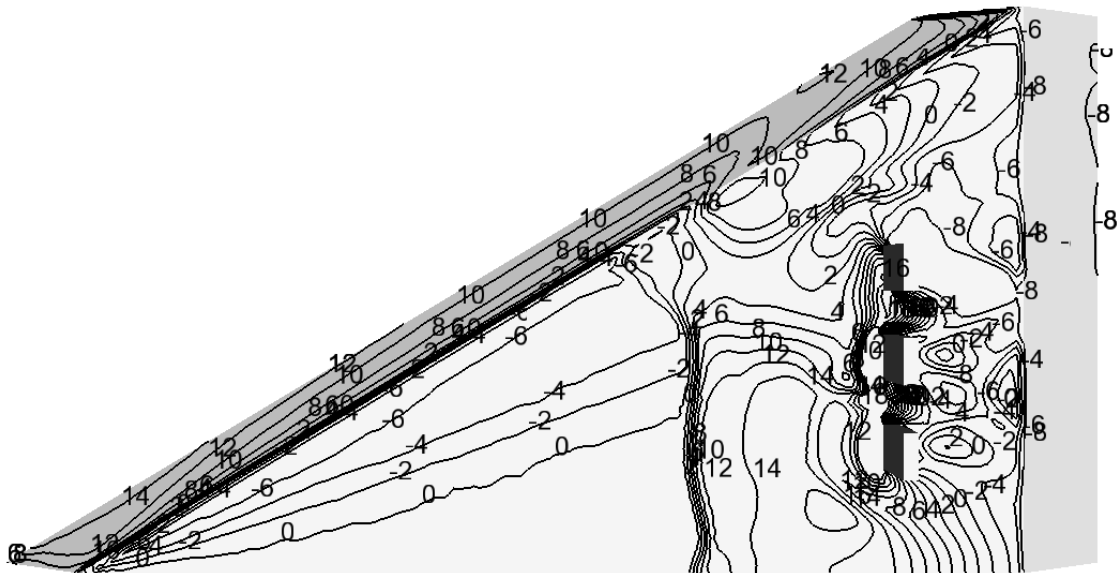

Figure 8. Baseline micro flap pressure contour levels on fin (psig).

As can be seen, the pressure levels are high in front of the micro flaps. The detached bow shock structure can been seen on both the flat plate and fin similar to the pin results. In addition, the smaller shock structure on the micro flaps just upstream of the flap can be seen as was the case in the pins.

Figure 8 shows the pressure contour levels on the fin in psig. The pressures in the detached shock region between the microflaps and the detached bow shock range from 4 to 14 psig. This large pressure difference creates a significant side load. The overall integrated side force generated by the configuration on the flat plate is about 6.5 lbs. This is lower than the single pin on the flat plate which produced 8.4 lbs as shown in Table 1. The two configurations have similar total cross-section area with the micro flaps having 60 mm^2 and the single pin having 64.5 mm^2. The microflaps themselves produced a similar level of axial force with 3.77 lbs vs 4.00 lbs for the single pin. The wake region on the fin behind the micro flaps is much more chaotic than with the pin configuration. The indirect effect produced by the pin gives a much cleaner pressure field on the fin than the direct effect produced by the micro flaps.
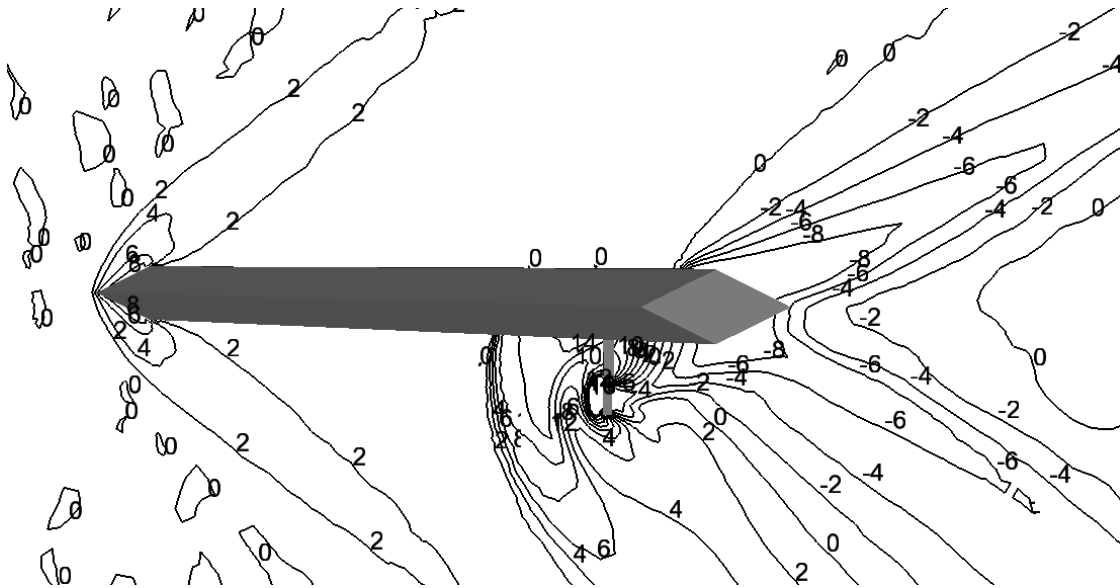

Figure 9. Baseline micro flap pressure contour levels on flat plate (psig).

Figure 9 shows the pressures on the flat plate produced by the micro flaps. Once again, the micro flaps do not appear to produce quite as clean of a pressure field behind the flaps as the pin structure. The detached bow shock is clearly seen on the flat plate.

IV. Conclusions

The results of the study show that the location, placement and shape and quantity of micro flaps can have a significant effect on the pressure field and result side force (control authority) on the fin. The paper will continue to develop the optimization of these parameters to understand the critical interactions for this type of fin-body interaction. These techniques are necessary fundamental research for application of devices to micro adaptive flow control of projectiles and other applications.

V. References

[1]Massey, K. C., McMichael, J., Warnock, T., Hay, F., "Mechanical Actuators for Guidance of a Supersonic Projectile", AIAA Paper 2005-4970, *AIAA Applied Aerodynamics Conference*, June 2005, Toronto, Ontario Canada.

[2]Massey, K. C., Guthrie, K. B., Optimized Guidance of a Supersonic Projectile Using Pin Based Actuators, AIAA Paper 2005-4966, *AIAA Applied Aerodynamics Conference*, June 2005, Toronto, Ontario Canada.

[3]Massey, K. C., Silton, Sidra I., Testing the Maneuvering Performance of a Mach 4 Projectile, AIAA Paper 2006-3649, *AIAA Applied Aerodynamics Conference*, June 2006, San Francisco, California.

[4]Bell, M., Watterson, J. K., Lisk, D., "A Numerical Study into a Local Protuberance Interaction with a Fin on a Supersonic Projectile", AIAA Paper 2009-1092, *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*, 5-8 January 2009, Orlando, Florida.